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TECHNICAL REPORT ARLCB-TR-82039

THE EFFECT OF VELOCITY ON THE SLIDING BEHAVIORS OF COPPER ALLOYS

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NOVEMBER 1982

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: ARLCB-TR-82039	2. GOVT ACCESSION NO.: AD-A123 869
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): THE EFFECT OF VELOCITY ON THE SLIDING BEHAVIORS OF COPPER ALLOYS	5. TYPE OF REPORT & PERIOD COVERED: Final
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): R. S. Montgomery	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: US Army Armament Research & Development Command, Benet Weapons Laboratory, DRDAR-LCB-TL, Watervliet, NY 12189	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: AMCMS No. 611102H600011; DA Project No. 1L161102AH60; PRON No. 1A2250041A1A
11. CONTROLLING OFFICE NAME AND ADDRESS: US Army Armament Research & Development Command, Large Caliber Weapon Systems Laboratory, Dover, NJ 07801	12. REPORT DATE: November 1982
	13. NUMBER OF PAGES: 24
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

To be published in technical journal Wear.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Friction	Sliding	M650 Projectiles
Wear	Chromium Electroplate	M549 Projectiles
Scuffing	Tantalum	Hardness
Metal Transfer	Rotating Bands	Velocity of Sliding
Copper Alloys	M483 Projectiles	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is a study of the sliding behaviors of a number of copper alloys and other metals at various velocities. The research was carried out using the "pin-on-disk" friction and wear machine used for the work in ARRADCON Technical Report ARLCB-TR-82018. The same three disk metals (AISI 4340 steel, chromium electroplate, and tantalum) and the same pin metals were also used. Previous experiments were at a sliding speed of 1.70 meters per second (m/s). In this

(CONT'D ON REVERSE)

20. ABSTRACT (CONT'D)

work sliding speeds of 3.05 m/s and 0.58 m/s were added for most of the alloys sliding on steel.

The amount of transferred metal generally increased with sliding velocity for copper alloys sliding on both steel and chromium electroplate but not for sliding on tantalum. The wear rates for the copper alloys sliding on steel usually increased as the sliding velocity increased from 0.58 m/s to 1.70 m/s, and then generally decreased as the sliding velocity increased still further from 1.70 m/s to 3.05 m/s sliding both on steel and tantalum. The wear rates sliding on chromium electroplate, on the other hand, remained about the same or increased as the sliding velocity increased from 1.70 m/s to 3.05 m/s. The coefficients of friction usually dropped as the speed of sliding was increased from 0.58 m/s to 1.70 m/s (only sliding on steel was investigated) and then usually remained about the same as the velocity was further increased from 1.70 m/s to 3.05 m/s.

It was not possible to correlate metal transfer, scuffing (rough transfer), or friction with the properties of the metal pair and, contrary to the situation at 1.70 m/s, there was no effect of hardness on wear at 3.05 m/s. At the faster sliding speed both wear and metal transfer of aluminum bronze and welded overlay band materials were not essentially different from the other copper alloys. (A difference had been found at a sliding speed of 1.70 m/s.)

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INTRODUCTION

The effect of velocity on sliding behavior is considered entirely thermal.[1,2] Archard,[3] in his widely accepted expression for wear, does not even have a term involving velocity. However, he specifies that both the probability of production of a wear particle and the flow pressure of the material must remain constant. Both of these, of course, would be affected by temperature and therefore velocity of sliding.

Hirst and Lancaster[2] studied the wear of 60/40 leaded brass on hardened steel using a pin and ring apparatus over a very wide range of speeds (0.001 to 100 m/s). They found that as speed increases the rate of wear first decreases to a minimum (at about 6 m/s) and then begins to increase again. They attributed this behavior to softening of the brass by frictional heating. Hayama[4] (as reported by Hirst and Lancaster) and Steijn,[5] using a more limited range of speeds, also found that the rate of wear decreased with speed at the lower sliding speeds. Gopinath et al[6] and Gopinath[7] reported on the wear of sintered iron sliding on steel at velocities used in the current work. They also found that wear rate first decreases with speed[7] and then slightly increases at higher speeds.[6] Multiple passes were used in all this work.

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[1]Bowden, F. P. and Tabor, D., The Friction and Lubrication of Solids, Oxford University Press (1950).

[2]Hirst, W. and Lancaster, J. K., "The Influence of Speed on Metallic Wear," Proc. Royal Soc. (London) 259, p. 228 (1960).

[3]Archard, J. F., "Contact and Rubbing of Flat Surfaces," J. Applied Physics, 24, p. 981 (1953).

[4]Hayama, F., Rep. Castings Res. Lab., Waseda University (7), p. 81 (1956).

[5]Steijn, R. P., "An Investigation of Dry Adhesive Wear," Trans. Amer. Soc. Mech. Engrs. (J. Basic Engineering) 81, p. 56 (1959).

[6]Gopinath, K., Rayudu, G. V. N., and Narayanamurthi, R. G., "Friction and Wear of Sintered Iron," Wear, 42, p. 245 (1977).

[7]Gopinath, K., "The Influence of Speed on the Wear of Sintered Iron-Based Materials," Wear, 71, p. 161 (1981).

There has been little work reported on the effect of sliding velocity on metal transfer. Rabinowicz and Tabor[8] studied the pickup of copper sliding on steel as well as other combinations of metals and concluded that it is independent of speed of sliding for clean metals. Their sliding speeds, which were in the range of 0.00003 to 0.005 m/s, were very much slower than those used in the present work. Hirst and Lancaster[2] in their study at higher sliding speeds found that the rate of metal transfer was equal to the wear rate over the whole range of speeds and remained equal despite the reversal in the wear rate trend at speeds above 1.0 m/s.

Bowden and Tabor[1] state that, in general, friction decreases as the temperature is raised (therefore velocity of sliding), but that the effect is slight unless heating is sufficient to affect the nature of surface films. They state, however, that if the temperature rise is due to frictional heating, it will be localized in the surface layers and so there may be more reduction in the coefficient of friction. They point out though that this does not happen to any marked degree with metals. In their second volume, Bowden and Tabor[9] described very high speed sliding of copper on steel and found very rapid reduction of the coefficient of friction followed by a leveling off. This same behavior was found by Montgomery[10] in the friction of projectiles (with copper alloy rotating bands) sliding on a steel cannon bore. As with

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[1]Bowden, F. P. and Tabor, D., The Friction and Lubrication of Solids, Oxford University Press (1950).

[2]Hirst, W. and Lancaster, J. K., "The Influence of Speed on Metallic Wear," Proc. Royal Soc. (London) 259, p. 228 (1960).

[8]Rabinowicz, E. and Tabor, D., "Metallic Transfer Between Sliding Metals; An Autoradiographic Study," Proc. Royal Soc. (London) A208, p. 455 (1951).

[9]Bowden, F. P. and Tabor, D., The Friction and Lubrication of Solids, Vol. II, Oxford University Press (1964).

[10]Montgomery, R. S., "Surface Melting of Rotating Bands," Wear, 38, p. 235 (1976).

the research of Bowden and Tabor, the sliding velocity reached very high values. Carignan and Rabinowicz[11] studied the sliding of copper and gilding metal, as well as a number of other metals on steel, at velocities from 30.5 to 152 m/s and found that the coefficient of friction as well as the wear rate decreased rapidly with speed. Montgomery[12,13] in his reports on the friction and wear research carried out at the Franklin Institute also at very high sliding speeds, reported the same general behavior. In addition, he reported that both friction and wear rate depended on the particular bearing pressure at the lower sliding speeds investigated (50 m/s). The behavior of the friction and the wear rate is doubtlessly due to a transition to melt lubrication at the very high sliding speeds.

EXPERIMENTAL METHOD

The present study was carried out using the "pin-on-disk" friction and wear machine used in the work previously reported.[14] The only difference was that the low velocity experiments (0.58 m/s) sliding on steel were made on a steel plate fixed to the rotating steel disk rather than the surface of the disk itself. The same three disk metals (AISI 4340 steel, chromium electro-plate, and tantalum) were used in the present study. Their properties are given in Table I.

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[11]Carignan, F. J. and Rabinowicz, E., "Friction and Wear at High Sliding Speeds," Trans. Am. Soc. Lube. Engrs., 23, p. 451 (1980).

[12]Montgomery, R. S., "Friction and Wear at High Sliding Speeds," Wear, 36, p. 275 (1976).

[13]Montgomery, R. S., "Friction of Gilding Metal Sliding on Chromium-Plated Steel," Wear, 50, p. 387 (1978).

[14]Montgomery, R. S., "The Sliding Behaviors of Copper Alloys," USA ARRADCOM Technical Report No. ARLCB-TR-82018, Benet Weapons Laboratory, Watervliet, NY, June 1982.

TABLE I. PROPERTIES OF THE DISK METALS

	4340 Steel	Chromium Electroplate	Tantalum
m.p. (°C)	1530°	1890°	3000°
Conductivity ($cal/cm^2/cm/sec/°C$)	0.108	0.16*	0.130
Elast. Mod. (kN/m^2)	200×10^6	110×10^6	186×10^6
Hardness (KHN)	235	1000	140
σ_u (kN/m^2)	744,000	103,000	758,000
σ_y (kN/m^2)	472,000	103,000	690,000
Elongation (%)	22	0	3

*From fused salt deposition.

Again the pin was plane-ended and 4.75 mm (0.187 inch) in diameter and the same pin metals were investigated. The pins were made of OFHC copper; sintered copper; two coppers containing iron (0.31 and 1.20 wt. %); two dispersion hardened coppers (Gildcop AL-20 and AL-60 with 0.4 and 1.1 wt. % aluminum oxide respectively); gilding metal (90-10 copper zinc alloy); an aluminum bronze; and welded overlay band materials from recovered M483 (gilding metal), M549 (copper), and M650 (copper) projectiles. The metal from the band of the recovered M483 projectile was not actually gilding metal and was not within specifications. It contained a large amount of aluminum. The compositions and properties of the pin metals are given in Tables II and III.

TABLE II. COMPOSITIONS AND PROPERTIES OF THE COPPER ALLOYS

	OFHC Cu	Sintered Cu	0.31% Fe Cu	1.20% Fe Cu	AL-20 Cu	AL-60 Cu	Gilding Metal
Cu (wt. %)	100.	99.82	99.44	97.92	99.6	98.9	90.0
Fe (wt. %)	0	0.012	0.313	1.197	-	-	0
Zn (wt. %)	0	0	0	0	-	-	10.0
Al_2O_3 (wt. %)	0	0	0	0	0.4	1.1	0
O_2 (wt. %)	0	0.09	-	-	-	-	-
Hardness (KHN)	88	73	70	77	174	175	85
m.p. (°C)	1083°				1082°	1082°	1021-1043°
Conductivity ($cal/cm^2/cm/sec/°C$)	0.958				0.843	0.768	0.450
Mod. of Elast. (kN/m^2)	$110x10^6$	$110x10^6$	$110x10^6$		$113x10^6$	$137x10^6$	$137x10^6$
σ_u* (kN/m^2)	220-240,000				470,000	520,000	258,000
σ_y* (kN/m^2)	69-76,000				370,000	450,000	69,000
Elongation (%)*	45-55				19	10	45

*With no cold work.

TABLE III. COMPOSITIONS OF ROTATING BAND AND ALUMINUM BRONZE ALLOYS

	Band Mat'l from M483	Band Mat'l from M549	Band Mat'l from M650	Aluminum Bronze
Cu (wt. %)	85.25	96.74	96.77	87.22
Fe (wt. %)	1.58	1.25	2.07	2.31
Zn (wt. %)	7.46	0	0.02	0
Al (wt. %)	5.21	0	0	9.72
Sn (wt. %)	0.34	0.99	0.68	0
Hardness (KHN)	132	144	137	146

A few of the experiments described in this report were made at a sliding speed of 0.58 m/s (23 inches/sec), but most were made at 3.05 m/s (120 inches/sec). Both of these correspond to projectile velocities close to the origin-of-rifling in a cannon where sliding is unlubricated metal-on-metal. The greater sliding speed is not fast enough so that there is a possibility of a molten film being formed on the sliding surface of the pin. The previously reported data obtained with a sliding speed of 1.70 m/s (67 inches/sec) were compared with the present data at 0.58 and 3.05 m/s to investigate the effect of velocity.

As in the previous experiments, the values of both instantaneous load and friction force were obtained from outputs of strain gages and recorded using a digital oscilloscope. Bearing pressures ranged between 55,000 kN/m^2 (8,000 psi) and 83,000 kN/m^2 (12,000 psi). The length of the pin projecting from the pin-holder before and after the experiment was measured for the wear

determination. Four experiments were usually made in a series and often two and sometimes more series were made with a particular pair. On the other hand, in the first few experiments only three determinations were made with each metal pair and, if the scatter in this data was not significant, another series was not made. Friction data were taken from the first portion of the experiment after almost full load was reached, but no data were taken at loads below 890 N (200 lbf). Metal transfer was estimated visually as none, very slight, light, moderate, heavy, or very heavy. The transferred metal was sometimes rough and this was noted.

Contact times were about 100 msec. This resulted in about two passes of the pin over the disk surface at the faster speed but friction data were never taken during the second pass. The second pass, of course, affected the wear determinations. At the slower speed (0.58 m/s) there was only one pass of the pin over the disk surface.

The data reported are for pins sliding on smooth, fresh surfaces. These disk surfaces were produced by removing all traces of transferred metal by abrading with 100 grit emery cloth at speed, then polishing with 400 grit emory cloth also at speed. In the later experiments, the disk was then wiped with soft paper wetted with methyl ethyl ketone and dryed with soft paper in order to remove any possible traces of organic contamination from the surface. In some preliminary experiments petroleum ether was used. In neither case did this final solvent cleaning make any appare _ difference.

DISCUSSION

A projectile in a cannon begins sliding from rest and rapidly gains speed. At some speed the surface of the rotating band melts and from that point the sliding is melt-lubricated and compatibility of the band material with the bore metal is unimportant. However, before this point compatibility is important and there is evidence that near the origin-of-rifling there has sometimes been scuffing and metal transfer with some band metals. This has lead to excessive metal loss from the bands and hence to wear of the bore at the muzzle and to inaccuracy. Because of the range of sliding speeds of projectiles in this critical region, the sliding behaviors of the copper alloys were studied at two different velocities sliding on chromium electroplate and tantalum and at three different velocities for most of the alloys sliding on steel.

The eleven copper alloys used as pin materials in this research are useful for studying the sliding behavior of projectile rotating bands. These alloys also are a series of metals with very similar melting points, chemical properties, and elasticities. On the other hand, their hardnesses and microstructures are very different and their ductilities quite different. Unfortunately, the propensity of copper alloys to work harden could have introduced a problem into efforts to find correlations with mechanical properties.

The three disk materials studied, tantalum, AISI 4340 steel, and chromium electroplate, are of interest or potential interest as bore surfaces in cannons. Most cannon bores are of gun steel which is closely approximated by AISI 4340; in some cannons the steel bore is protected by a coating of

chromium electroplate; and bore liners of tantalum or of tantalum alloys are being considered because of their resistance to "erosion". In addition, these three metals are very different in their chemical, physical, and mechanical properties but are all quite immiscible with copper.

Metal Transfer

Data from the sliding experiments are given in Tables IV, V, and VI and wear as a function of metal transfer at a sliding speed of 3.05 m/s is given in Figure 1. Sometimes there was great variation in the amount and character of metal transferred to the rotating disk with a single metal pair. This doubtlessly was a result of the very small sliding area and the very short time of sliding. It raises the possibility that heavy and rough transfers would have been obtained with more of the copper alloys if more experiments had been performed. In any case, at a sliding speed of 3.05 m/s heavy or very heavy transfer occurred with AL-20 and AL-60 coppers, sintered copper, and band material from the M650 projectile all sliding on 4340 steel. This condition also occurred with aluminum bronze and band materials from the M483, M549, and M650 projectiles sliding on tantalum, and with OFHC copper, copper containing 0.31 percent iron, and Al-60 copper sliding on chromium electroplate.

While there was a tendency for more transfer to occur at higher wear rates, heavy and very heavy transfer occurred even at zero wear (measured to the precision of the experiment). The least squares intercept (i.e. wear at no metal transfer) was at 0.0044 mm wear which is consistent with wear measured to the nearest 0.025 mm in the experiment. There was about the same correlation of wear with metal transfer if experiments resulting in none, very slight, or light transfer were not considered. Even rough transferred metal

TABLE IV. AVERAGE RESULTS FROM SLIDING EXPERIMENTS ON STEEL

		0.58 m/s	1.70 m/s	3.05 m/s
OFHC Cu	$\bar{f}$	0.37 ± 0.02	0.31 ± 0.03	0.33 ± 0.05
	Wear (mm)	0.2	0	0
	Wear Rate (mm/m)	0.3	0	0
	Transfer	None	None to Light	V. Slight to Moderate
	Rough	No	No	No
Sintered Cu	$\bar{f}$	0.58 ± 0.02	0.39 ± 0.02	0.31 ± 0.02
	Wear (mm)	0.2	0.8	0.9
	Wear Rate (mm/m)	0.3	0.5	0.3
	Transfer	V. Slight	V. Slight to Heavy	V. Slight to Heavy
	Rough	No	Occasionally	Occasionally
0.31% Fe Cu	$\bar{f}$	0.39 ± 0.03	0.30 ± 0.02	0.34 ± 0.02
	Wear (mm)	0.2	2.4	0
	Wear Rate (mm/m)	0.3	1.4	0
	Transfer	None	None to Light	V. Slight to Light
	Rough	No	No	No
1.20% Fe Cu	$\bar{f}$	0.62 ± 0.04	0.40 ± 0.01	0.38 ± 0.04
	Wear (mm)	0.2	1.6	1.0
	Wear Rate (mm/m)	0.3	0.9	0.3
	Transfer	V. Slight	V. Slight to Light	V. Slight to Moderate
	Rough	No	No	Occasionally

TABLE IV. AVERAGE RESULTS FROM SLIDING EXPERIMENTS ON STEEL (CONT'D)

		0.58 m/s	1.70 m/s	3.05 m/s
AL-20 Cu	$\bar{f}$	0.54 ± 0.05	0.33 ± 0.01	0.37 ± 0.01
	Wear (mm)	0	0	0
	Wear Rate (mm/m)	0	0	0
	Transfer	V. Slight	None to Light	Moderate to Heavy
	Rough	Yes	No	Occasionally
AL-60 Cu	$\bar{f}$	0.63 ± 0.04	0.33 ± 0.01	0.36 ± 0.01
	Wear (mm)	0.5	0	3.2
	Wear Rate (mm/m)	0.9	0	1.1
	Transfer	Moderate	Moderate to V. Heavy	Heavy to V. Heavy
	Rough	Yes	Occasionally	Yes
Gilding Metal	$\bar{f}$	0.53 ± 0.02	0.45 ± 0.02	0.46 ± 0.03
	Wear (mm)	0.2	0.5	0.7
	Wear Rate (mm/m)	0.3	0.3	0.2
	Transfer	Light	Light to Moderate	Light to Moderate
	Rough	No	No	No

1.70 m/s data reported in Reference 14.

TABLE V. AVERAGE RESULTS FROM SLIDING EXPERIMENTS ON TANTALUM AND CHROMIUM

		On Ta		On Cr	
		1.70 m/s	3.05 m/s	1.70 m/s	3.05 m/s
OFHC Cu	$\bar{f}$	0.33 ± 0.02	0.32 ± 0.03	0.52 ± 0.05	0.46 ± 0.03
	Wear (mm)	0.4	0.7	0.2	1.8
	Wear Rate (mm/m)	0.2	0.2	0.1	0.6
	Transfer	V. Slight to Light	None to Moderate	None	None to Heavy
	Rough	No	Occasionally	No	Occasionally
Sintered Cu	$\bar{f}$	0.35 ± 0.03	0.36 ± 0.05	0.36 ± 0.03	0.43 ± 0.02
	Wear (mm)	0.3	0.3	0	–
	Wear Rate (mm/m)	0.2	0.1	0	–
	Transfer	None to V. Slight	None	None	Moderate
	Rough	No	No	No	Occasionally
0.31% Fe Cu	$\bar{f}$	0.33 ± 0.01	0.30 ± 0.02	0.38 ± 0.03	0.40 ± 0.02
	Wear (mm)	1.0	0.3	1.2	5.5
	Wear Rate (mm/m)	0.6	0.1	0.7	1.8
	Transfer	V. Slight to Heavy	None	V. Slight to Moderate	Moderate to Heavy
	Rough	No	No	Occasionally	Yes
1.20% Fe Cu	$\bar{f}$	0.38 ± 0.03	0.36 ± 0.03	0.35 ± 0.02	0.22 ± 0.02
	Wear (mm)	1.0	0.3	0.2	0
	Wear Rate (mm/m)	0.6	0.1	0.1	0
	Transfer	None to V. Slight	None to V. Slight	None	None
	Rough	No	No	No	No

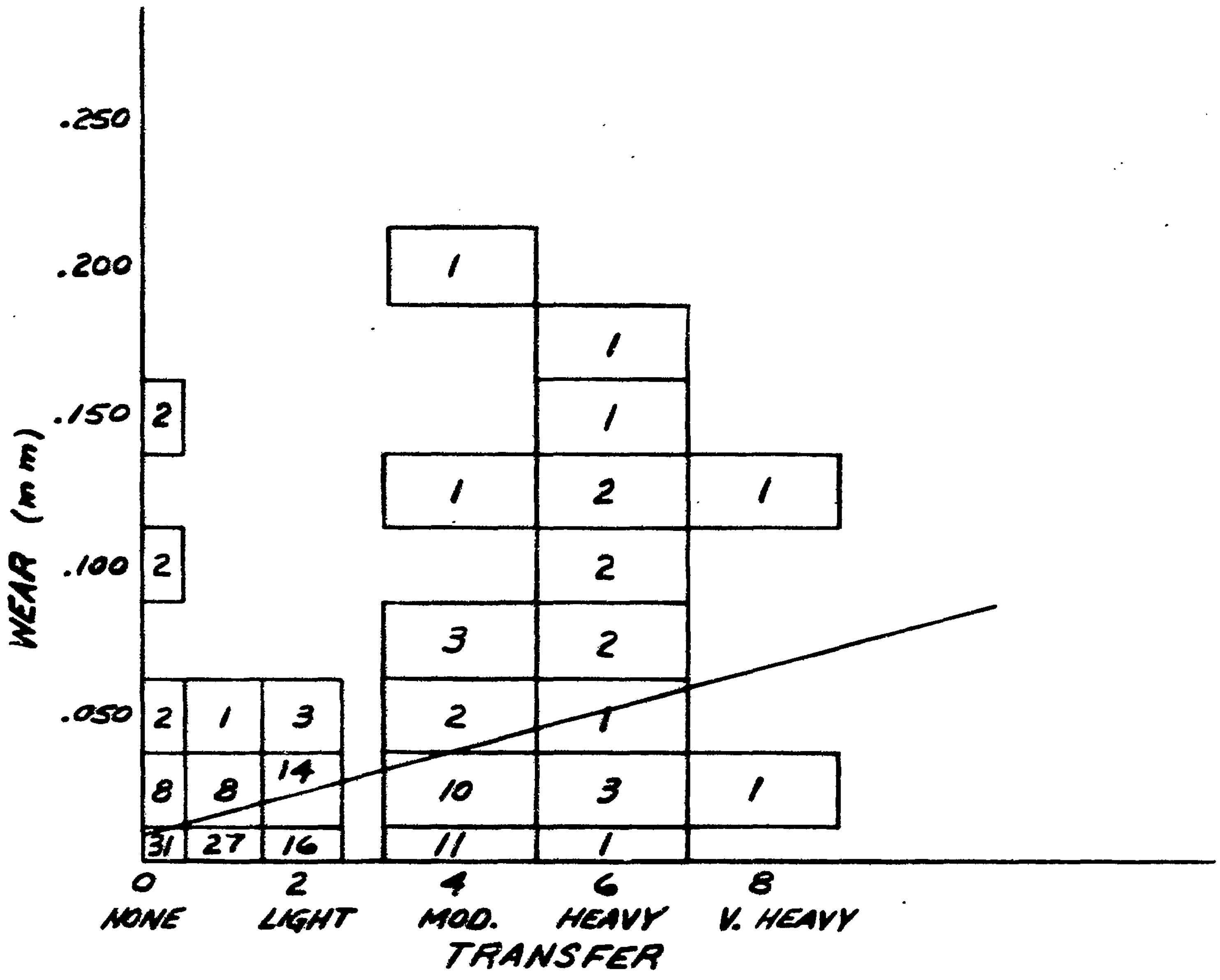
TABLE V. AVERAGE RESULTS FROM SLIDING EXPERIMENTS ON TANTALUM AND CHROMIUM (CONT'D)

		On Ta		On Cr	
		1.70 m/s	3.05 m/s	1.70 m/s	3.05 m/s
AL-20 Cu	$\bar{f}$	0.31 ± 0.02	0.38 ± 0.03	0.38 ± 0.02	0.36 ± 0.03
	Wear (mm)	0.3	0	0	0.3
	Wear Rate (mm/m)	0.2	0	0	0.1
	Transfer	V. Slight	None to V. Slight	None to V. Slight	None
	Rough	No	No	No	No
AL-60 Cu	$\bar{f}$	0.36 ± 0.01	0.28 ± 0.03	0.39 ± 0.02	0.53 ± 0.05
	Wear (mm)	0.2	0.3	0	2.2
	Wear Rate (mm/m)	0.1	0.1	0	0.7
	Transfer	V. Slight	None to V. Slight	None	None to Heavy
	Rough	No	No	No	No
Gilding Metal	$\bar{f}$	0.37 ± 0.01	0.36 ± 0.03	0.27 ± 0.02	0.34 ± 0.03
	Wear (mm)	0.8	0.3	0	0.3
	Wear Rate (mm/m)	0.5	0.1	0	0.1
	Transfer	Light to Moderate	Light	None	None
	Rough	Occasionally	No	No	No

1.70 m/s data reported in Reference 14.

TABLE VI. AVERAGE RESULTS FROM SLIDING EXPERIMENTS WITH ALUMINUM BRONZE AND THE WELDED OVERLAYS

		On Steel		On Ta		On Cr	
		1.70 m/s	3.05 m/s	1.70 m/s	3.05 m/s	1.70 m/s	3.05 m/s
Aluminum Bronze	$\bar{f}$	0.38 ± 0.02	0.41 ± 0.02	0.29 ± 0.03	0.32 ± 0.03	0.32 ± 0.02	0.38 ± 0.02
	Wear (mm)	0.5	0.3	1.8	3.5	0.2	0
	Wear Rate (mm/m)	0.3	0.1	1.1	1.2	0.1	0
	Transfer	V. Slight to Light	Moderate	Moderate to V. Heavy	Moderate to Heavy	None	V. Slight
	Rough	No	No	Occasionally	Yes	No	No
M483 Proj. Band Mat'l	$\bar{f}$	0.35 ± 0.01	0.34 ± 0.02	0.40 ± 0.02	0.43 ± 0.02	0.25 ± 0.04	0.32 ± 0.01
	Wear (mm)	0.9	0.8	3.4	0	0.1	0.17
	Wear Rate (mm/m)	0.5	0.3	2.0	0	0.06	0.06
	Transfer	V. Slight to Light	Light	V. Slight to Heavy	V. Slight to Heavy	None to Light	Light
	Rough	No	No	Occasionally	Occasionally	No	No
M549 Proj. Band Mat'l	$\bar{f}$	0.29 ± 0.03	0.26 ± 0.02	0.29 ± 0.02	0.31 ± 0.01	0.32 ± 0.02	0.32 ± 0.02
	Wear (mm)	1.0	1.5	6.0	4.0	0	0
	Wear Rate (mm/m)	0.6	0.5	3.5	1.3	0	0
	Transfer	V. Slight to Moderate	Light	Light to Heavy	Moderate to Heavy	None	None
	Rough	Occasionally	Occasionally	Occasionally	Occasionally	No	No
M650 Proj. Band Mat'l	$\bar{f}$	0.40 ± 0.02	0.43 ± 0.01	0.28 ± 0.02	0.26 ± 0.02	0.38 ± 0.03	0.32 ± 0.04
	Wear (mm)	0.7	1.0	0.8	0.7	0.1	0.2
	Wear Rate (mm/m)	0.4	0.3	0.5	0.2	0.06	0.06
	Transfer	Moderate	Moderate to Heavy	Light to V. Heavy	Light to Heavy	None to Light	None to Moderate
	Rough	Yes	Yes	Yes	Yes	No	Occasionally



NUMBERS IN THE BOXES ARE THE NUMBER OF EXPERIMENTS WITH THOSE RESULTS.

Figure 1. Wear as a Function of Metal Transfer.

was not usually associated with high wear or heavy transfer. In about 35 percent of the cases of a rough deposit, wear was measured as zero and metal transfer in the majority of cases where a rough deposit was obtained was only moderate. This is essentially the metal transfer behavior of the copper alloys sliding at 1.70 m/s reported previously.[14]

The amount of transferred metal generally increased with sliding velocity at least up to a speed of 3.05 m/s for copper alloys sliding on both steel and chromium electroplate, but when sliding on tantalum the transfer was constant or decreased somewhat with increasing velocity. Perhaps this is because of the very high melting point of tantalum. It is not the result of thermal conductivity because steel has a lower and chromium a higher conductivity.

Mutual solubility with the disk metal, melting point, elasticity, and the chemical properties of all the copper alloys were about the same, but metal transfer was sometimes very different. Therefore, these could not be controlling factors and there was no correlation with either hardness or ductility. Small amounts of iron in the copper did not lead to transfer or scuffing even when sliding on steel. Even microstructure and crystalline directionality do not seem to be important factors controlling metal transfer. (Photomicrographs of the microstructures and X-ray results are given in Reference 14.)

Sliding velocity probably had no effect on the roughness of the transferred metal. If the particular copper alloy tended to give rough

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[14]Montgomery, R. S., "The Sliding Behaviors of Copper Alloys," USA ARRADCOM Technical Report No. ARLCB-TR-82018, Benet Weapons Laboratory, Watervliet, NY, June 1982.

transferred metal at the lower sliding speed, it also tended to give rough transferred metal at the higher speed.

<u>Wear</u>

Contrary to the situation at a sliding velocity of 1.70 m/s,[14] the behaviors of aluminum bronze and the welded overlay band materials at 3.05 m/s were not essentially different from the other copper alloys investigated. In addition, there was no correlation of wear with hardness of the copper alloys sliding at 3.05 m/s as there was with most of the alloys sliding at 1.70 m/s. Harder alloys often wore more than the softer. As before, wear could not be correlated with any other mechanical property.

The wear rates (wear per unit distance of sliding) for the copper alloys sliding on steel usually increased as the sliding velocity increased from 0.58 m/s to 1.70 m/s. (Data on some of the alloys were not obtained at the lower velocity.) The wear rates for the copper alloys sliding on both steel and tantalum generally decreased as the sliding velocity increased from 1.70 m/s to 3.05 m/s. The wear rates, however, for the copper alloys sliding on chromium electroplate (with the highest thermal conductivity of the disk materials) remained about the same or increased as the sliding velocity increased from 1.70 m/s to 3.05 m/s. It seems reasonable that the low speed mechanism would extend to higher sliding velocities with a higher thermal conductivity disk metal; there should be less surface temperature increase and therefore less softening.

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[14]Montgomery, R. S., "The Sliding Behaviors of Copper Alloys," USA ARRADCOM Technical Report No. ARLCB-TR-82018, Benet Weapons Laboratory, Watervliet, NY, June 1982.

Friction

As reported in Reference 14 for sliding at 1.70 m/s, the coefficients of friction at 3.05 m/s could not be correlated with any bulk property. From the experiments with the alloys sliding on steel at 0.58 m/s, the coefficients usually dropped as the speed of sliding increased from 0.58 m/s to 1.70 m/s. The coefficients then usually remained about the same for all the disk metals as the velocity further increased from 1.70 m/s to 3.05 m/s. As an exception to this, there was a large drop in friction for copper containing 1.20 percent iron sliding on chromium. The latter was associated with significantly greater wear and metal transfer.

Although the effect of load on the coefficients of friction was not investigated in more than a few cases at a sliding velocity of 3.05 m/s, some examples are plotted in Figure 2. In these cases the coefficients were high at low loads and decreased as the load increased. In two out of the three cases there was little further change with load at loads greater than 890 N (200 lbf). This is the same general behavior reported in Reference 14 for sliding at 1.70 m/s.

CONCLUSIONS

1. As reported for a sliding velocity of 1.70 m/s,[14] it was not possible to correlate metal transfer, scuffing (rough transfer), or friction with the properties of the metal pair. Contrary to the situation at 1.70 m/s, there was no effect of hardness on wear at 3.05 m/s. (Only sliding on steel and not

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[14]Montgomery, R. S., "The Sliding Behaviors of Copper Alloys," USA ARRADCOM Technical Report No. ARLCB-TR-82018, Benet Weapons Laboratory, Watervliet, NY, June 1982.

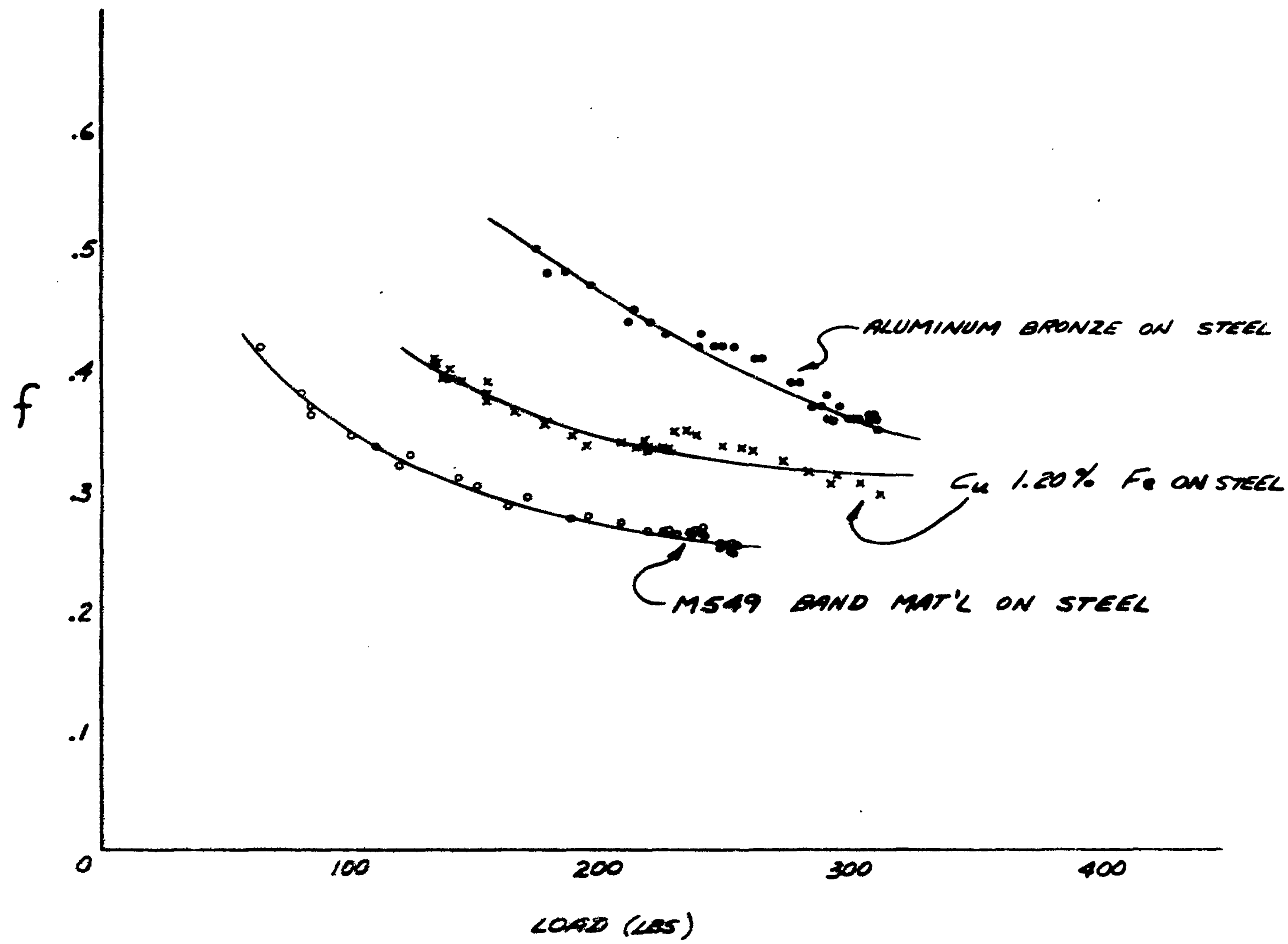

Figure 2. Effect of Load on Coefficients of Friction at 3.05 m/s.

all the copper alloys were investigated at 0.58 m/s. The properties of the copper alloys including hardness could not be correlated with their sliding behaviors at this lower speed for the alloys investigated.)

2. Contrary to the situation at 1.70 m/s, both metal transfer and wear of the aluminum bronze and the welded overlay band materials were not essentially different from the other copper alloys investigated at a sliding speed of 3.05 m/s. (These alloys were not studied at a sliding speed of 0.58 m/s.)

3. The amount of transferred metal generally increased with sliding velocity, at least up to a speed of 3.05 m/s, for copper alloys sliding on both steel and chromium electroplate, but they showed about the same or somewhat less transfer sliding on tantalum at the higher velocity. Sliding velocity probably had no effect on the roughness of the transferred metal.

4. The wear rates for the copper alloys sliding on steel usually increased as the sliding velocity increased from 0.58 m/s to 1.70 m/s. However, they generally decreased as the sliding velocity increased still further from 1.70 m/s to 3.05 m/s sliding both on steel and tantalum. The wear rates for the copper alloys sliding on chromium electroplate, on the other hand, remained about the same or increased as the sliding velocity increased from 1.70 m/s to 3.05 m/s.

5. From the experiments with the alloys sliding on steel at 0.58 m/s, the coefficients of friction usually dropped as the speed of sliding was increased from 0.58 m/s to 1.70 m/s; they then usually remained about the same for all the disk metals as the velocity further increased from 1.70 m/s to 3.05 m/s.

6. As reported for a sliding velocity of 1.70 m/s,[14] small amounts of iron in the copper alloys did not seem to result in scuffing and high metal transfer even when sliding on steel. Mutual solubility with the disk metal and position in the periodic table did not control metal transfer and scuffing of the copper alloys studied. Also, metal transfer was not the first step in the production of loose wear particles. As before, while there was a tendency for more transfer to occur at higher wear rates, heavy and very heavy transfer did occur at very low wear rates. Heavy and very heavy transfer were not usually associated with high wear and rough deposits.

7. The metals actually used for rotating bands, i.e. gilding metal and the welded overlays, wore very little sliding on chromium electroplate at 3.05 m/s. Relatively high wear was experienced with OFHC copper, copper containing 0.31 percent iron and AL-60 copper.

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[14]Montgomery, R. S., "The Sliding Behaviors of Copper Alloys," USA ARRADCOM Technical Report No. ARLCB-TR-82018, Benet Weapons Laboratory, Watervliet, NY, June 1982.

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